

A THEORETICAL EVALUATION OF ALUMINUM GEL PROPELLANT TWO-PHASE FLOW LOSSES ON VEHICLE PERFORMANCE

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SUMMARY:

A one-dimensional model of a hydrocarbon/ Al/O_2 (gaseous) fueled rocket combustion chamber has been developed to study secondary atomization effects on propellant combustion. This chamber model has been coupled with a two-dimensional, two-phase flow nozzle code to estimate the two-phase flow losses associated with solid combustion products. Results indicate that moderate secondary atomization significantly reduces propellant burnout distance and Al_2O_3 particle size; however, secondary atomization provides only moderate decreases in two-phase flow induced I_{sp} losses. Despite these two-phase flow losses, a simple mission study indicates that aluminum gel propellants may permit a greater maximum payload than the hydrocarbon/ O_2 bi-propellant combination for a vehicle of fixed propellant volume. Secondary atomization was also found to reduce radiation losses from the solid combustion products to the chamber walls, primarily through reductions in propellant burnout distance.

TECHNICAL DISCUSSION:

Gel propellants, in which a solid constituent, composed of very fine particles ($\sim 1\text{-}5\ \mu\text{m}$ in diameter), is suspended in a gelled liquid carrier, offer potential performance and/or safety advantages over conventional liquid and solid propellants in rocket applications. Theoretical performance evaluations show that gel propellants may provide increases in specific impulse and/or propellant density over conventional liquid propellants, thereby increasing mission ΔV or payload.¹⁻⁵ It should be noted, however, that these theoretical studies on gelled propellants do not include performance losses associated with gel combustion such as increased propellant combustion times, radiation heat transfer from condensed combustion products to the chamber walls, and nozzle two-phase flow losses. Since gel-induced I_{sp} efficiency losses of 1.5-4% are sufficient to eliminate the benefits of gel propellants in a volume and mass constrained vehicle,⁴ the above losses must be determined before the performance of gel propellants can be accurately evaluated.

Since propellant combustion times and solid combustion product size, and therefore two-phase flow losses, are proportional to initial droplet size, small droplets are desirable. Although fine spray atomization of gelled propellants is difficult to achieve, research has indicated that small droplets may be produced through secondary atomization of large droplets, a process in which a droplet shatters into a number of smaller droplets due to rigid particle shell formation and internal vaporization of the liquid carrier fluid.^{6,7} Little work has been done, however, to evaluate gel performance losses and secondary atomization effects on these losses.

A one-dimensional model of a JP-10/Al/O₂(gaseous) fueled rocket combustion chamber has been developed to evaluate secondary atomization effects on propellant combustion.⁸ In brief, a radially uniform spray, consisting of four droplet size classes, enters the combustion chamber and burns in a process incorporating liquid carrier burnout, droplet secondary atomization, aluminum agglomerate heat up and combustion, two-phase particle flow, and radiation from solid combustion products to the chamber walls. A schematic of this combustion process for a single droplet, with and without secondary atomization, is presented in Fig. 1. Because the post-secondary atomization droplet size distributions are currently unknown, droplets are assumed to fragment into a given number of equal-sized droplets where the number of secondary droplets produced per initial droplet is defined as the fragmentation ratio, β , which is treated as a model parameter. This combustor code is used in conjunction with a two-dimensional two-phase nozzle performance code (SPP)⁹ to determine two-phase flow losses in the engine nozzle and propellant mass flowrate through the engine.

RESULTS:

To simulate an upper-stage booster, the one-dimensional combustor and SPP codes were exercised using the chamber diameter, pressure, flow rates, aluminum mass loading, and nozzle geometry presented in Table 1. Because of comparable total propellant aluminum mass loadings, a solid motor nozzle profile (Extended Delta)⁹ was used for the nozzle geometry. Moderate secondary atomization ($\beta=5$) was found to significantly reduce propellant burnout distance (40%) and final Al₂O₃ residual diameter (60%). Results also indicate that radiation losses to the chamber walls are a function of secondary atomization, primarily through changes in propellant burnout distance. These radiation losses range from 0.4-5% of the sensible enthalpy entering the combustion chamber and should be even less in larger engines where the flow optical thickness is greater than the case considered here.

It should be noted, however, that Al₂O₃ residual size predicted by the combustor code may not be correct for nozzle performance calculations. Since the Al₂O₃ particles are molten throughout most of the nozzle, and because small particles accelerate more quickly than large particles, particle size may increase through coagulation. Similarly, additional Al₂O₃ may be produced through the recombination of gas-phase radicals as the exhaust gases cool during expansion, resulting in the nucleation of additional particles and/or growth of previously formed particles. Particle size may also decrease due to shear breakup of droplets, particularly in the throat region of the nozzle. Because of these uncertainties in Al₂O₃ particle size, two methods of estimating particle size, which should bound the true particle size, are used in the evaluation of nozzle performance. In the first method, we use an Al₂O₃ particle size in the nozzle that is determined by the one-dimensional combustor code, making secondary atomization the primary mechanism governing particle size. In the second method, secondary atomization is assumed to have no effect on mean particle size; rather, coagulation, particle surface growth, and shear induced droplet breakup are assumed to be the dominate mechanisms affecting particle size. Based on predictions of Al₂O₃ particle size in solid rockets,^{9,10} a particle mass mean diameter, D_{43} , of 5.6 μm was determined for this second case.

A comparison of two-phase flow losses for the above methods of determining Al_2O_3 particle size are presented in Fig. 2 for a 60 wt% aluminum gel. As can be seen, secondary atomization may reduce two-phase flow losses but does not affect two-phase flow losses as significantly as propellant burnout distance. Using the second, more conservative, method of estimating Al_2O_3 particle size, engine I_{sp} was calculated for a range of aluminum mass loadings and propellant mixture ratios and compared with I_{sp} calculations for a JP-10/ O_2 bi-propellant. Figure 3 show that I_{sp} decreases with increasing aluminum loading and that the maximum I_{sp} mixture ratio becomes richer, as has been predicted by other studies.⁵

Because I_{sp} alone does not indicate mission performance, a simple mission study of a vehicle of fixed propellant volume and dry mass was conducted, incorporating two-phase flow losses. Maximum payload was calculated for different propellant mixture ratios and aluminum mass loadings using the mission/vehicle parameters, which approximate an upper-stage LEO-GEO orbital transfer, and payload mass equation presented in Table 2.⁵ From this analysis, shown in Fig. 4, it was found that maximum payload increases with aluminum mass loading up to an aluminum mass loading of 60% and then decreases as additional aluminum is added. The maximum payload for the aluminum gels was found to be 7% greater than that of the JP-10/ O_2 bi-propellant combination.

CONCLUSIONS:

The above results indicate that only moderate secondary atomization is required to effectively reduce overall propellant burnout distance and final Al_2O_3 residual size. Preliminary results indicate that secondary atomization provides only moderate decreases in two-phase flow induced I_{sp} losses. A simple mission study indicates that hydrocarbon/Al gels may offer payload increases over a hydrocarbon/ O_2 bi-propellant for a vehicle of fixed propellant volume and dry mass. It should be noted that vehicle mass limitations and propellant density effects on propellant tank size, and therefore vehicle dry mass, could alter the above performance results.⁴

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Table 1. Engine Geometry and Operating Conditions

| | |
|--------------------|------------|
| Chamber Diameter | 0.19 m |
| Chamber Pressure | 3867 kPa |
| Throat Diameter | 0.109 m |
| Expansion Ratio | 30.8 |
| Gel Flow Rate | 10.78 kg/s |
| Al Mass Loading | 60% |
| Oxidizer Flow Rate | 11.75 kg/s |

Table 2. Mission/Vehicle Parameters and Payload Mass Equation

| | |
|---------------------------|----------------------|
| Mission ΔV | 4267.2 m/s |
| Vehicle Propellant Volume | 56.63 m ³ |
| Vehicle Dry Mass | 2761.6 kg |

$$M_{PL} = \frac{\rho_{prop} \cdot Vol_{prop} - M_{dry} [\exp(\Delta V / I_{sp} g) - 1]}{[\exp(\Delta V / I_{sp} g) - 1]}$$

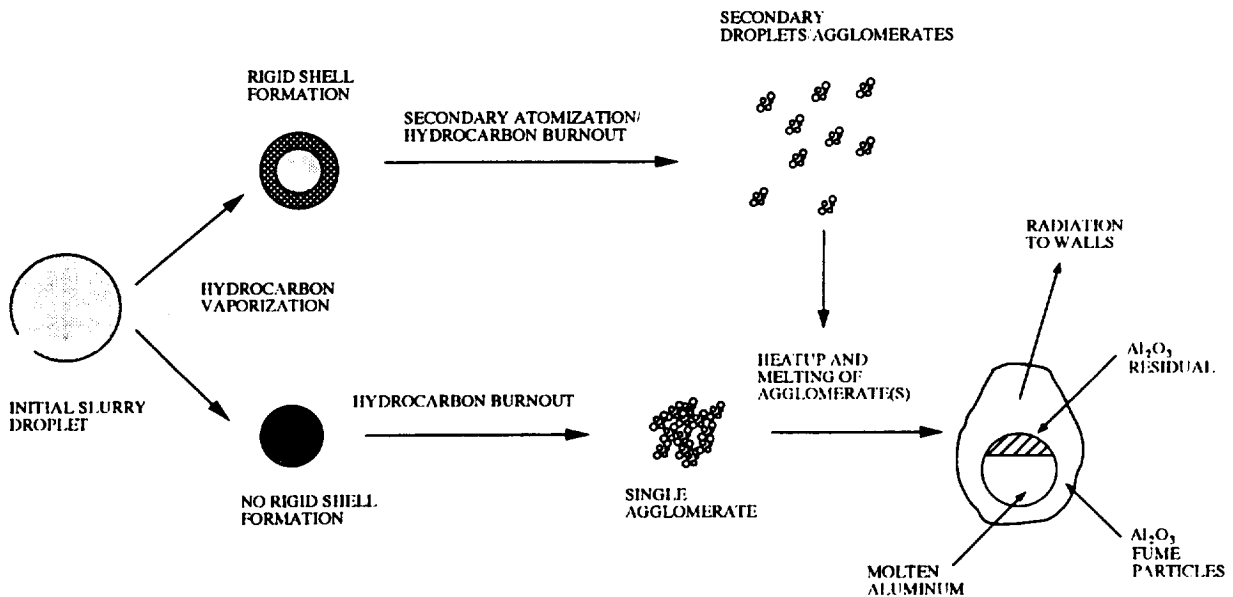


Figure 1. Schematic of the gel combustion process in a rocket combustion chamber, with and without secondary atomization.

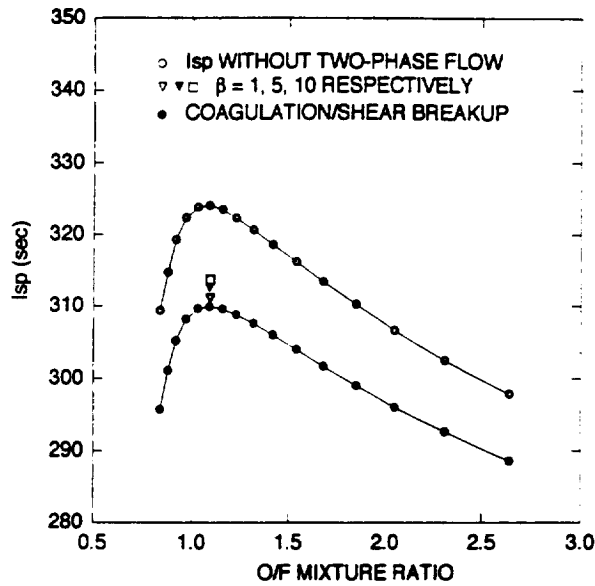


Figure 2. Effects of two-phase flow on engine I_{sp} for a 60 wt% Al gel. Data are for two methods of determining Al_2O_3 particle size; size predicted by one-dimensional model and size based on Al_2O_3 particle coagulation and shear-induced particle breakup.

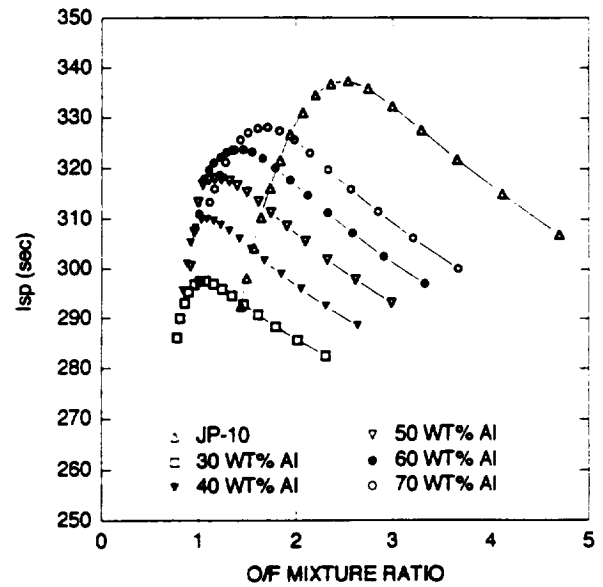


Figure 3. Engine I_{sp} as a function of propellant mixture ratio and gel aluminum weight percentage.

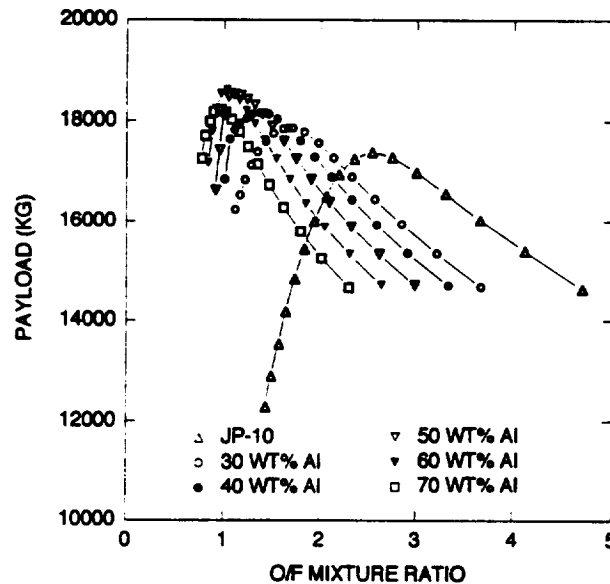


Figure 4. Maximum payload for a vehicle of fixed propellant volume and dry mass as a function of mixture ratio and gel aluminum weight percentage.